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Effect of mine characteristics on life cycle impacts of US surface coal mining

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Abstract
Purpose This study's aim was to understand the effect of mine characteristics on cradle-to-gate life cycle impacts of surface coal mining in the USA. Five bituminous coal strip mines were used as case studies. The study assessed the life cycle water use, land use, energy use, abiotic resource depletion, and climate change impacts.
Methods The study employed the general principles of the ISO 14040-49 series LCA standards, modifying them where necessary. The functional unit was defined as "one tonne of processed coal at the mine gate." The relative mass–energy–economic value method, with some modification, was used to scope the product system. Data were obtained from environmental impact statements, coal mining permit applications, government reports, and published literature. Life cycle impact assessment (LCIA) included classification and characterization but no normalization, grouping, or weighting, to avoid ambiguity. In this work, mid-point characterization models were preferred over damage-oriented (end-point) characterization models because of their high levels of uncertainties. The LCIA also included sensitivity analysis.
Results and discussion For the studied mines, life cycle potential water use impact is 178 l/tonne of processed coal at the mine gate. The potential land use, energy use, abiotic resource depletion, and climate change impacts range from 3 to 10 m^2 year/tonne, 97 to 181 MJ/tonne, 7.8 to 9.4 kg Sb-eq./tonne, and 38 to 92 kg CO_2-eq./tonne, respectively. Land use impacts depend mainly on land for coal extraction activities and the climatic conditions of a region, which affects the vegetation recovery rate, following reclamation. Economies of scale significantly influence land use, energy use, abiotic resource depletion, and climate change impacts. Geology, which determines stripping ratio, coal quality, and coalbed methane, affects land use, climate change, and energy use impacts, particularly energy for overburden removal, reclamation, and beneficiation.
Conclusions The data show that large-scale mining operations have lower life cycle impacts due to economies of scale, which results in lower energy use. Also, land use impacts, measured by land occupation, are affected by geologic conditions. This study provides insight into sources of variability in life cycle impacts of coal mining. The authors recommend timely reclamation to minimize land occupation impacts, as well as adoption of large-scale production, where appropriate, for efficient use of land occupied by mine facilities.

Keywords Abiotic resource depletion · Climate change · Coal mining · Energy use · Land use · Life cycle assessment · Water use

1 Introduction

Coal generates about one half (48.5% in 2008) of the electricity used in the USA (EIA 2009a) and 39% of electricity worldwide (World Coal Institute 2005). Projections up to 2030 predict that increases in coal consumption

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for electricity generation and for coal-to-liquids plants, expected to be constructed in the future, will result in an annual coal production growth rate of about 0.6% (EIA 2009c). Other than its use in electricity generation, coal is a vital feedstock in other industrial processes such as steel making, cement production, and paper making.

Surface coal mining operations account for about two thirds (69.5% in 2008) of total coal production in the USA (EIA 2009b). Surface mining methods are important for coal extraction as they are amenable to high productivity, allow good recovery rates, and have lower safety hazards, compared to the underground mining systems. However, surface coal mining has significant environmental impacts that need to be properly assessed in order to exploit coal reserves in a sustainable manner.

All the relevant environmental sustainability tools should be used to evaluate sustainability of coal mining. While there is a general shift by the coal mining industry toward embracing environmental sustainability, there is still limited use of environmental sustainability evaluation tools in the coal mining industry. The inherent limited scope of various sustainability assessment tools affects the quality and effectiveness of sustainability reporting in the mining industry (Ditsele 2010). Even though the life cycle assessment (LCA) framework is currently believed to address mining issues poorly (Lindeijer 2005), when adapted appropriately, the technique can provide valuable information about mining processes. The holistic approach inherent in LCA enables impacts across temporal and spatial scales to be brought together in one framework.

The objective of this work was to understand the effect of mine characteristics on cradle-to-gate life cycle impacts of surface coal mining in the USA. Cradle-to-gate life cycle impacts of surface coal mining were estimated using the general principles of ISO 14040-49 series of standards for life cycle assessment and adapting them to the peculiar situation of coal mining. The study was aimed at giving an understanding of the effect of mining methods on the overall impacts of coal, using data from five strip mining operations in the USA. This work assessed water use, land use, energy use, abiotic resource depletion for energy sources, and climate change impacts and used them to compare the mines. While other impact categories, such as acidification, eutrophication, human toxicity, ecotoxicity, and photochemical oxidation, are important and relevant, the five were chosen because of their unique relevance to coal mining. Processes downstream of mining have not been included in this study because a lot of LCA work has been done in those areas as evidenced by the existence of comprehensive databases on coal use, especially in electricity generation. A sensitivity analysis was conducted to evaluate the effect of input variation on the overall results. The authors recommend strategies to address some potential impacts.

There have been a number of LCA studies on electricity generation, which is the major consumer of coal (Kim and Dale 2005; Babbitt and Lindner 2005; Schreiber et al. 2009; Froese et al. 2010). In these studies, generally, coal mining is treated as a single unit process in the electricity generation system, and as such, the detail on mine characteristics and mining processes is limited. In some instances, impacts that are important in mining are excluded. There is the tendency to use national or regional coal mining averages with limited consideration of the mining method (surface or underground), geology, and other mine characteristics (Ruether et al. 2004; Babbitt and Lindner 2005; Schreiber et al. 2009). Electricity generation LCAs mostly include energy use in mining and associated emissions but leave out some impacts that are predominant in the mining stage, such as land use. For instance, Froese et al. (2010) only evaluated greenhouse gas emissions. As far as the authors know, none of the studies on electricity generation includes land use impacts from mining.

LCA studies focusing on coal mining include the evaluation and comparison of environmental performance of South African coal products with their economic values (Mangena and Brent 2006), an LCA of coal produced by longwall mining in Poland (Czaplicka-Kolarz et al. 2004), and an LCA of anthracite coal production in Vietnam (Chinh et al. 2007). There are also coal life cycle inventory (LCI) data contained in some commercially available data sets (e.g., PE International 2006). The LCI of Babbitt and Lindner (2005) includes the coal mining stage. Chinh et al. (2007) and Babbitt and Lindner (2005) use aggregate data for coal from surface and underground mining methods, and therefore, they do not clearly reflect environmental flows and impacts that are specific to surface coal mining. While Mangena and Brent (2006) have separate assessments for surface and underground mines and cover a number of impact categories important to coal mining, their study characterizes and normalizes the impacts in the context of the South African situation. The commercially available data sets on coal extraction and processing tend to be generated from industry-wide statistics on coal production such as those published by the International Energy Agency or US Energy Information Administration. The US LCI database (www.nrel.gov/lci/database) has cradle-to-gate LCIs for anthracite coal from underground and surface mines, bituminous coal from underground and surface mines, and lignite from surface mines in the USA. The inventories do not include some environmental flows (e.g., CO_2 emissions from mining equipment and electricity generation) that are important to coal mining. In essence, there is very little work on the effect of mine characteristics and processes such as geology and mining method on the life cycle impact of surface coal mining in the USA.

This work provides an initial insight into the effect of mine characteristics and mining methods on life cycle

impacts using five study mines. Even though the sample size is small, the mines were selected to illustrate the causes of variability. The USA, unlike other western large coal producers, has a significant amount of small-scale producers who do not use large draglines in coal production. The mines in this study reflect the diversity of mining methods that affect life cycle impacts.

This paper is organized into six parts. The next section describes the product system while Section 3 presents the LCI. Section 4 presents the results of LCIA. The last two sections are the conclusions and references cited.

2 Surface coal mining product system

2.1 Case study mines

Five surface mines designated as mines A, B, C, and D were used to evaluate the LCA impacts of surface coal mining. Mine A is a mine complex made up of the Black Mesa (mine A1) and Kayenta (mine A2) mines, which operated in two contiguous mine leases located in the Hopi and Navajo Nation tribal lands in northern Arizona. Overburden (material overlying the coal seam) and interburden (material lying between coal seams) materials are removed primarily using draglines. Partings of 3 to 15 ft thickness are removed using shovels, front-end loaders, and dump trucks, while those less than 3 ft are removed using dozers. Shovels, front-end loaders, and dump trucks are used to move the exposed coal and transport it to the coal preparation plants. Cottage Grove Mine (mine B) is located in Saline County, Illinois. Production from the mine is by means of shovels, front-end loaders, dozers, and haulage trucks. Coal from the mine is processed at the nearby Willow Lake Mine's Preparation Plant. Cottonwood Creek Mine (mine C) is located in Bates County in western Missouri. Overburden material is blasted and removed using dozers, excavators, front-end loaders, and dump trucks. Coal is ripped by dozers and loaded into trucks for transportation to the plant where it is crushed, gob material removed, and then screened to size. The on-site processing plant uses power supplied by a 1.65-MMBtu/h diesel generator. Hume Mine (mine D) is, also, located in Bates County, Missouri. The mine uses dozers, excavators, front-end loaders, and trucks. Processing involves crushing, sizing, and removal of non-coal material in a portable crushing facility. Table 1 shows the production parameters of the mines (Ditsele 2010).

2.2 Product system and scoping

The functional unit for this study was defined as, "one tonne of processed coal at the mine gate." Figure 1 shows the initial product system for the cradle-to-gate surface coal mining system. A two-step approach was used to scope the system. The first step was to determine if the inputs or unit processes contribute significantly to impact categories that can be characterized on a local or global scale. The second step was to apply quantitative methods based on the relative mass–energy–economic value (RMEE) method (Raynolds et al. 2000) to scope the unit processes in Fig. 1.

It was necessary to treat water and land use differently in both steps. The importance and impact of water and land use are local issues, and hence, any attempt to spatially aggregate water and land use will be controversial. Potential land use and water use impacts from coal mining activities can only be assessed in the context of the local mine environment. In this study, water and land use impacts were assessed by considering only activities within the mining permit area. In step 2, water use from exploration and mine development were disregarded as they are likely to be insignificant on a functional unit basis, compared to the operational phases mines. These are capital unit processes and are routinely disregarded in LCA studies (Baumann and Tillman 2004). Land use scoping over the temporal scale of mining (exploration, development, extraction, preparation, and reclamation—Fig. 1) was based on the RMEE concept with cutoff of 0.01%. The remaining unit processes were scoped based on RMEE method with a cutoff of 0.01% (Table 2). The scoped unit processes were

Table 1 Study mine descriptions

Mine	Mine A	Mine B	Mine C	Mine D
Average coal seam thickness (m)	2.00	2.00	0.66	0.89
Average overburden thickness (m)	11.6	27.0	14.6	17.1
Energy content (MJ/tonne)	29,784	28,337	25,353	24,888
Ash content	7.53%	17.1%	16.0%	15.9%
Sulfur	0.66%	3.8%	3.7%	3.5%
Coalbed methane (kg/tonne)	0.78	0.66	0.75	0.75
Annual production (million tonnes)	11.8	0.61	0.18	0.056
Reserves (million tonnes)	728.0.	7.0	1.4	1.6
Permit land area (ha)	2.61×10^4	3.62×10^2	2.81×10^2	2.63×10^2

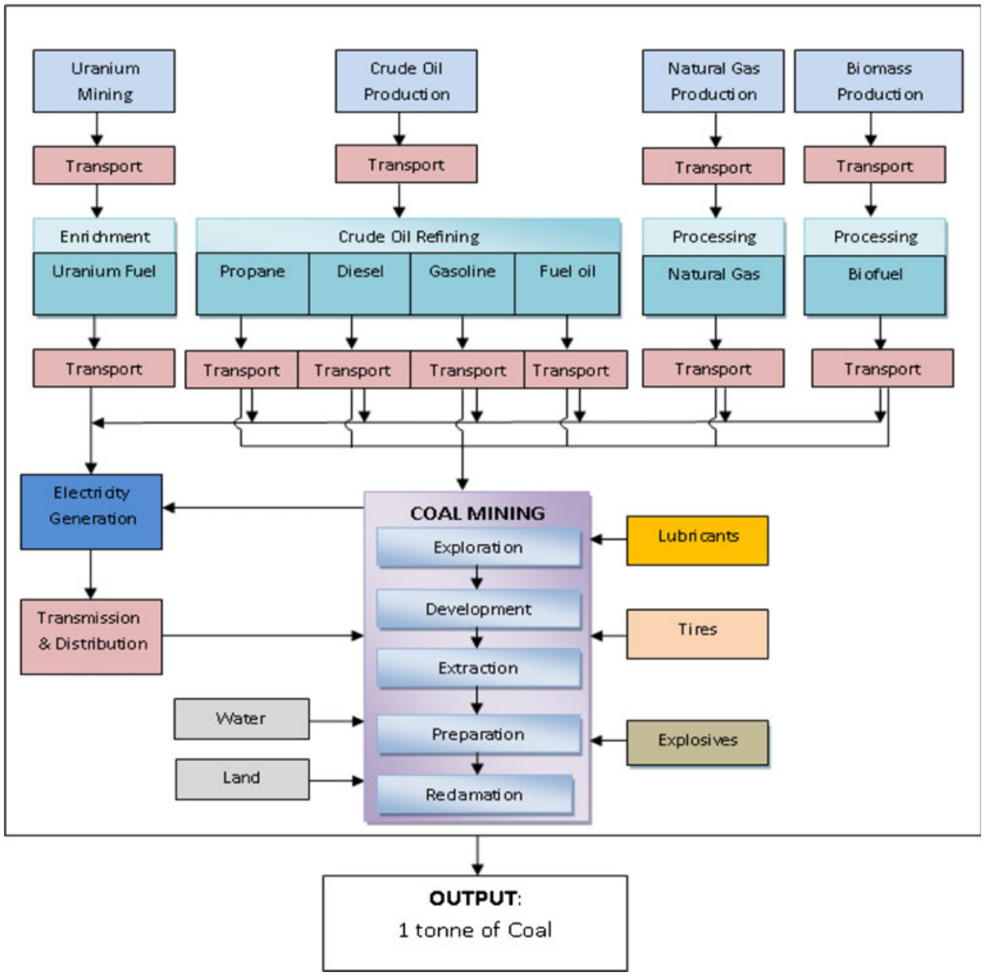


Fig. 1 Initial product system

aggregated to fit data availability. Figure 2 shows the final product system used to determine the LCI.

3 Life cycle inventory analysis

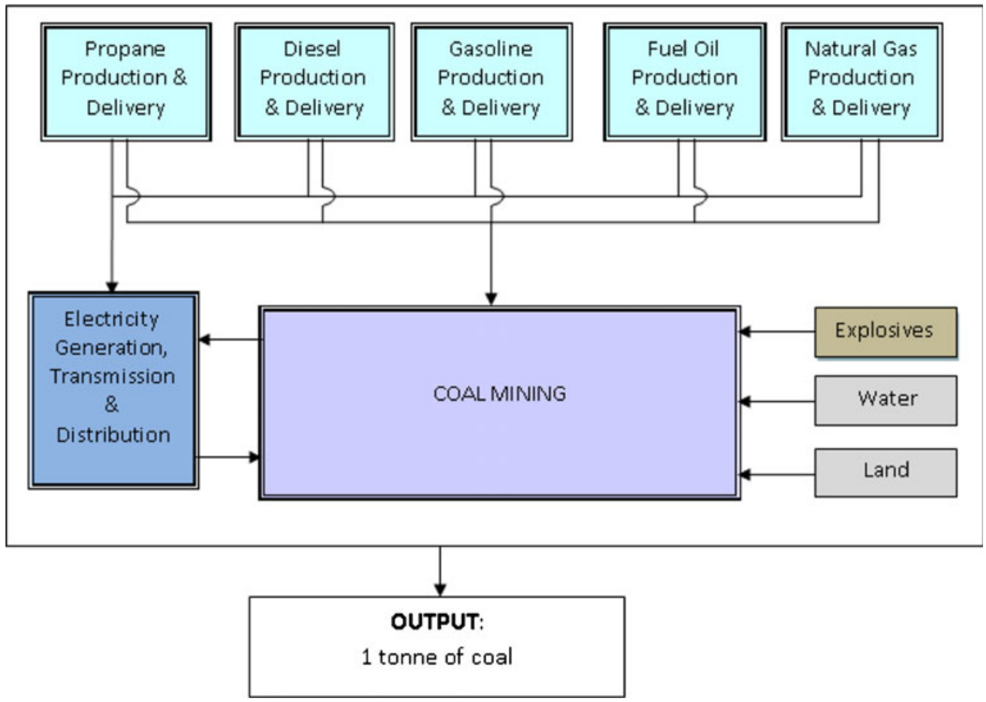
The LCI results are shown in Table 3. Land use was determined by dividing the total land area that is likely to be disturbed throughout the life of a mine (land already disturbed by construction of facilities and coal extraction, plus coal resource areas that are yet to be disturbed) by the total reserves for the mine. Electricity, diesel, gasoline, and propane consumption data in mine A were sourced from the environmental impact statement for the mine complex (OSMRE 2008). For the other mines, energy use was estimated from models based on the major equipment and the operating schedules. The models used included equipment manufacturer models; the greenhouse gases, regulated emissions, and energy use in transportation model (Argonne 2009); and InfoMine (2009) (Ditsele 2010). The energy content and emission factor of ammonium nitrate–fuel oil (ANFO) mixture was assumed to be 803.64 kcal/kg (Aimone 1992) and 0.17 tonnes of CO_2/tonne (Day et al. 2010), respectively. Greenhouse gas emissions from the fuel use were calculated using the carbon content, oxidation factors, and emission factors for the fuels (EPA 2005). Water use data were only available for mine A (OSMRE 2008).

Table 2 Cutoff criteria used in the RMEE scoping

Parameter	Functional unit value	Cutoff value based on 0.01%	Remarks
Mass (tonne)	1	0.0001 tonne	Bituminous coal
Energy content[a] (MJ)	27,695	2.8	Illinois basin coal
Economic value[a]	\$44.65	\$0.004	Illinois basin coal spot price

[a]Illinois basin coal energy content of 11,800 Btu/lb and 31 December 2009 spot price of \$44.65/ton (EIA 2010)

Fig. 2 Final product system



4 Life cycle impact assessment

Table 4 shows the life cycle impact assessment results. The next three subsections discuss the assessment methods and results. Care was taken to ensure data uncertainty was reduced to a minimum by addressing completeness (through scoping) and relevance. Where mine-specific data were not available, temporal, geographical, and technological relevance were considered to select appropriate data for the operations (e.g., use of relevant coal basin data in place of mine-specific data and use of state electricity generation resource mix where source of power was not specified).

Table 3 Life cycle inventory

Mine	Mine A	Mine B	Mine C	Mine D
Inputs from technosphere				
Electricity (kWh)	13.96	1.75	2.62	2.54
Diesel (*l*)	2.71	10.72	13.67	21.02
Gasoline (*l*)	0.16	0.17	0.23	0.17
Propane (*l*)	0.32			
Explosives (ANFO) (kg)	1.81	4.24	6.91	4.66
Inputs from nature				
Total energy input (MJ)	97.1	97.6	120.7	181.1
Coal (kg)	1,036.94	1,016.65	1,015.34	1,038.05
Natural gas (kg)	30.72	28.70	36.19	55.87
Petroleum (kg)	8.91	30.68	39.06	59.72
Water (*l*)	178.00			
Land area (m^2)	0.22	0.38	1.79	1.23
GHG emissions to air				
CO_2 (g)	17,907.30	36,410.06	45,495.52	70,888.49
CH_4 (g)	797.61	697.85	793.70	822.58
N_20 (g)	0.14	0.11	0.12	0.21
Product output				
Bituminous coal (tonnes)	1.00	1.00	1.00	1.00
Energy content (MJ/tonne)	29,784	28,337	25,353	24,888

Table 4 Life cycle impacts

Impact category	Impact per functional unit (1 tonne of coal)				
	Mine A	Mine B	Mine C	Mine D	Average
Water use (*l*)	178	–	–	–	–
Land use (m^2 year)	4.9	2.9	10.0	9.0	6.7
Energy use (MJ)	97.1	97.6	120.7	181.1	124.1
Abiotic resource depletion (kg Sb-eq)	7.80	8.06	8.38	9.38	8.41
Climate change (kg CO_2-eq.)	37.9	53.9	65.4	91.5	62.2

4.1 Water and land use impacts

The authors did not use characterization factors for water use impacts. Total water consumption (see Table 3) was used as an indicator for water use impact.

In this study, land occupancy, accounting for land area and duration of occupation, was used to assess life cycle land use impacts. Spitzley and Tolle (2004) suggest that land occupancy is the product of area and duration before restoration. This approach assumes that land reclamation will restore the land to equal quality as the pre-use quality. This is valid for US surface coal mining since the Surface Mining Control and Reclamation Act (SMCRA) of 1977, the regulatory regime, requires coal mine sites to be reclaimed to original use or alternate land uses be equal or better than pre-mining uses. It was assumed that the reclaimed land reaches desired performance 5 years after the initial revegetation for mines in Missouri and Illinois (mines B, C, and D) and 10 years for mines in Arizona (mine A) as per the SMCRA regulations. Where year-by-year data on disturbed and reclaimed areas were not available, the total coal resource areas disturbed and reclaimed were divided among the years based on annual production rates. Ditsele (2010) contains details of and data used for land use impact estimation.

The results are shown in Table 4. Mine C, which has the largest land area disturbance of 1.8 m^2/tonne (see Table 3), has the highest potential land use impact of 10 m^2 year/tonne of coal followed closely by mine D. The high potential land use impacts for these two mines are due to their relatively high stripping ratios[1] (22:1 and 19:1) and small scales of production. The lower productivity leads to long mine lives and hence a longer land occupation.

4.2 Energy use impacts

This study used energy intensity values as indicators for energy use impacts (see Table 4). The biggest contributor to energy use impact for mine A is electricity use (72%), while diesel use dominates the impact for the other mines (77–81%). Explosive use contributes between 6% (mine A) and 19% (mine C), which reflects the differences in stripping ratios for the mines. Higher stripping ratio implies more overburden, which requires more explosives. The energy use impacts due to gasoline and propane use are only marginal (maximum of 1.5% and 0.9% for gasoline and propane, respectively).

4.3 Abiotic resource depletion impacts

Abiotic depletion potentials developed by the Center of Environmental Science of Leiden University (CML) were used in the assessment. The CML 2001 characterization factors based on mid-point modeling for soft coal, natural gas, and crude oil are 0.00671 kg Sb-eq./kg, 0.0187 kg Sb-eq./m^3, and 0.0201 kg Sb-eq./kg, respectively (Guinée 2002). The characterization modeling, in this study, is based on reserves and rates of extraction on a global scale. The results are shown in Table 4.

There is a positive correlation between energy use and abiotic resource depletion, with mine D having the highest abiotic resource depletion impact. The contribution of individual fossil fuels to a mine's overall abiotic resource depletion impact depends on its energy source portfolio (see Table 3). For instance, mine A has 2% of its resource depletion impact from petroleum and 89% from coal. This is due to the mines' low use of petroleum derived fuels and heavy reliance on electricity, which is generated, partly, from coal (the main earthmovers are electric-powered draglines). On the other hand, the heavy use of diesel-powered earthmovers in mines B, C, and D results in relatively high resource depletion impact contribution from petroleum (8–13% of total resource depletion impact). As is the case with energy use, the abiotic resource depletion impacts are linked to the benefits of economies of scale.

4.4 Climate change impacts

Global warming potential (GWP) using mid-point characterization modeling over a 100-year time horizon was used in this study. The GWPs for methane and nitrous oxide

[1] Stripping ratio is the ratio of overburden (material overlying the coal seam) to the amount of coal.

Table 5 Performance ranking

	Ranking of indicators[a]			
	Mine A	Mine B	Mine C	Mine D
Land use	2	1	4	3
Energy use	1	2	3	4
Abiotic resource depletion	1	2	3	4
Climate change	1	2	3	4

[a]Mines are ranked from 1 to 4 with the best performance (lowest impact) given a rank of 1

were estimated to be 25 and 298 kg CO_2-eq., respectively (IPCC 2007). The results are shown in Table 4

Mine A has the lowest potential climate change impact (38 kg CO_2-eq./tonne), followed by mines B, C, and D with 54, 65, and 92 kg CO_2-eq./tonne, respectively. Once again, there is positive correlation between energy use and climate change impacts and negative correlation between production scale and climate change impacts. For mine A, most (51%) of the impact is from coalbed methane emissions whereas emissions from diesel use dominate that of other mines (65%, 69%, and 76% for mines B, C, and D, respectively). Given that flaring the coalbed methane could potentially reduce climate change impacts by 89% (Ditsele 2010), flaring the coalbed methane in mine A could significantly reduce its climate change impacts.

4.5 Performance ranking and sensitivity

The mines were then ranked for performance based on land use, energy use, resource depletion, and climate change impacts (Table 5). For the three impacts dependent on energy efficiency of the mines, ranking in decreasing order of performance are mines A, B, C, and D. Mine B performs better than mine A with respect to land use, primarily because the climate in the western USA requires a longer reclamation period to the restore the land. Overall, economies of scale determine efficiency and influence the impacts.

The study examined the influence of the electricity mix by assuming the same electricity resource generation (2005 US) mix (EPA 2009). Table 6 shows the energy use, resource depletion, and climate change impacts using this assumption. As can be seen from the results, the relative performance of the mines with respect to resource depletion and climate change does not change. There is a reversal in relative performance of mines A (102.4 from 97.1 MJ/tonne) and B (99.9 from 97.6 MJ/tonne) with respect to energy use. The reversal is more a function of the similar performance of the two mines than any change from the resource mix. This, however, underscores the importance of evaluating the sensitivity of LCA results to changes in assumptions.

5 Conclusions

The following conclusions are drawn from this work:

- Life cycle water use impact for the production of coal from surface mining in the USA has been estimated to be 178 l/tonne of coal. However, the assessment for this impact category was limited by data availability for some of the case study mines and the small sample size.
- Potential land use impacts range from 3 to 10 m^2 year/tonne, with an average of 6.7 m^2 year/tonne. Land use impacts are dominated by land affected by coal extraction activities. The influence of climatic conditions on the recovery of vegetation, following land reclamation, is an important factor for life cycle land use impacts.
- Potential energy use impacts per tonne of coal range from 97 to 181 MJ/tonne, with an average of 124 MJ/tonne. The most significant contributors to this are electricity use for mine A and diesel use for mines B, C, and D.
- Potential abiotic resource depletion impacts (assessed based on the depletion of coal, natural gas, and petroleum) range from 7.8 to 9.4 kg Sb-eq./tonne, with an average of 8.4 kg Sb-eq/tonne. The heavy use of electricity in mine A leads to 89% of the impact due to coal depletion. On the other hand, mines B, C, and D have 8–13% of their impact due to petroleum depletion.

Table 6 Life cycle impacts using 2005 US electricity resource generation mix

Impact category	Impact per functional unit (1 tonne of coal)				
	Mine A	Mine B	Mine C	Mine D	Average
Energy use (MJ)	102.4	99.9	129.3	177.7	127.3
Abiotic resource depletion (kg Sb-eq)	7.73	8.10	8.40	9.38	8.40
Climate change (kg CO_2-eq.)	39.1	54.1	64.2	90.8	62.1

- Potential climate change impacts range from 38 to 92 kg CO_2-eq./tonne with an average of 62 kg CO_2-eq./tonne. Coalbed methane is more important for the climate change impacts assessed for mine A because of the relatively high energy efficiency. Climate change impacts for mines B, C, and D are dominated by CO_2 emissions from diesel use.
- Mine B has the best performance on potential land use impacts, and it is followed by mines A, D, and C in that order. For energy use, abiotic resource depletion and climate change impacts, mine A has the lowest impact indicators, followed by mines B, C, and D in that order.
- Economies of scale have a marked influence on the land use impacts (particularly, the efficient use of land occupied by mine facilities), energy use impacts, abiotic resource depletion impacts, and climate change impacts.
- Factors arising out of geological conditions, such as stripping ratios, influence the land use impacts, particularly the land disturbances in the coal resource areas. Stripping ratios determine the energy requirements for overburden removal and reclamation efforts. Geology also determines the methane emission rates from strata (which contributes to climate change impacts) and the quality of coal in the ground (which has a bearing on the beneficiation energy necessary to meet the specifications desired by customers).

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